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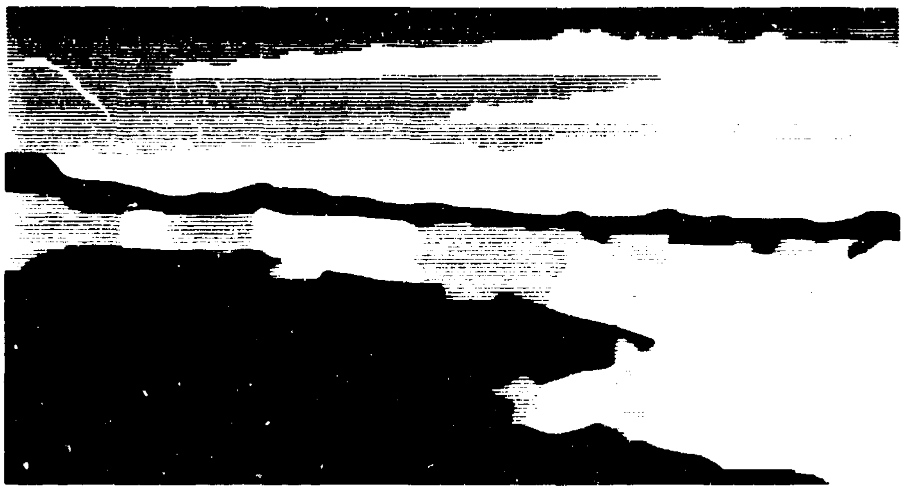

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Applications of RQMD to Bose-Einstein Correlations

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Abstract

Source size parameters measured via two-particle interferometry in experiment NA44 for 200 GeV/nucleon S+Pb collisions are compared to calculations using the RQMD event generator. Reasonable agreement is found in most cases. Based on this agreement, the model is used to study some of the interesting details of the collision dynamics which are not easily measured.

Introduction

In the last decade many experimental measurements of source size parameters from two particle interferometry have become available[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Quantitative interpretations of these size parameters are complicated by resonance decays, correlations between the position and momentum of a particle, and Coulomb interactions between the identical particles. We can improve our understanding of these influences using an event generator. The event generator is used to generate a one-body phase space distribution of particles. From this information, the two particle correlation function can be approximately calculated using a Wigner function formalism[14, 15]. In this study, the RQMD (relativistic quantum molecular dynamics) model[16, 17] will be used. RQMD is a microscopic phase-space approach, based on resonance and string excitation and fragmentation with subsequent hadronic collisions[16, 17]. In principle, the same technique could be used with other event generators.

In the simplest view of boson interferometry, there is a static source with no correlations between the momentum and position of a particle. These assumptions lead from a source position distribution of the form

$$\rho(r) \propto \exp(-\frac{r^2}{2R^2_{gauss}}), \tag{1}$$

where r is the position of a particle's last interaction and R_{gauss} is a size parameter, to a correlation function of the form

$$C_2(q) = 1 + \lambda \exp(-q^2 R^2_{gauss}), \tag{2}$$

where q is the two-particle momentum difference and λ is a parameter whose value is one in the ideal case. When there are correlations between the position and momentum of a particle in the "source" which from they are emitted, the size parameter which comes from fitting data to eq. 2 can not be directly interpreted as the source size parameter R which appears in equation 1. This problem and the associated problems with resonance decays and Coulomb corrections will be examined below.

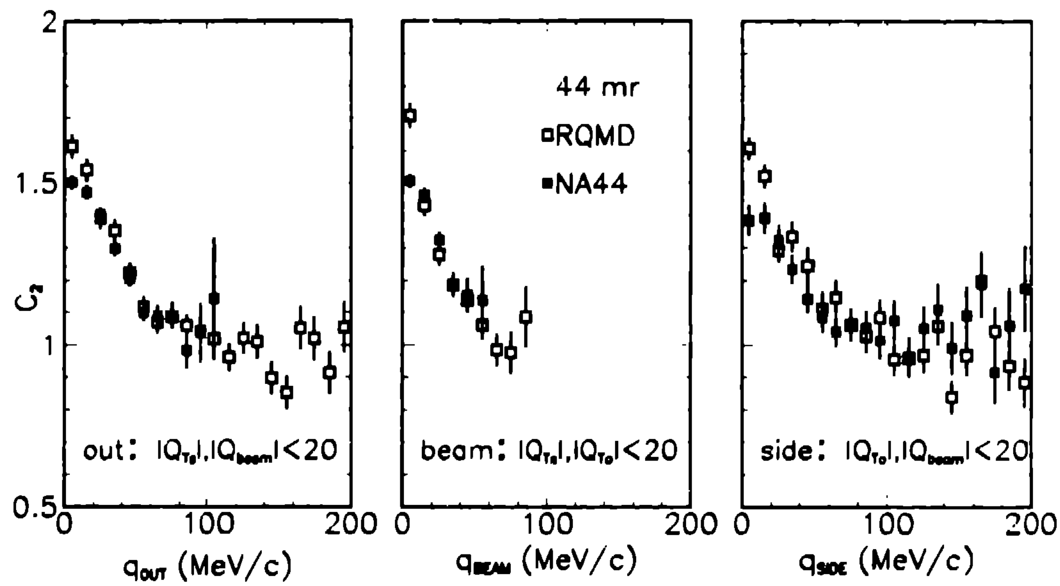

Figure 1: For 200 GeV/nucleon S+Pb collisions, the comparison of NA44 data and calculations based on the RQMD event generator. Calculations for the q_{out}, q_{beam}, and q_{side} components of the momentum difference are shown. Results for the 44 mr ("low p_T") spectrometer setting are shown.

Experimental Results

In this paper, only the experimental results from Cern experiment NA44[7, 10, 12, 13] will be compared to the calculations. However, similar calculations have been compared to several other experiments including NA35[11, 18], E859[19], and E814[20].

The NA44 Focusing Spectrometer[7], which uses two dipole magnets and three quadrupoles, covers a momentum range of ±20% around its central momentum setting. For the data shown here, the central momentum settings are 4 GeV/c (lab) for pions and 6 GeV/c for kaons. The two spectrometer angle settings used for π^+, 44 mrad and 131 mrad, are referred to as low p_T ($< p_T > \approx$ 150 MeV/c) and high p_T ($< p_T > \approx$ 450 MeV/c), respectively. For the data discussed here, the tracking and time-of-flight uses three scintillator hodoscopes whose time resolution is ≈ 100 ps, with a Cherenkov beam counter[21] for the time-of-flight start ($\sigma \approx$ 35 ps).

The NA44 data have been analyzed in terms of three components[22, 23] of the two-particle momentum difference ($\vec{q} = \vec{p_1} - \vec{p_2}$). The data are analyzed in the frame in which the z-component of the pair momentum ($p_{z1} + p_{z2}$) is zero (the longitudinal center of mass system, or "LCMS"). The momentum difference is resolved into a component

(q_{beam}) parallel to the beam direction and a component perpendicular to the beam direction. The perpendicular component is further resolved into q_{out} parallel to the sum of the pair momentum and q_{side}, which is perpendicular to the sum and to the beam. Three corresponding source size parameters (R_{beam}, R_{out}, R_{side}) are simultaneously fit to measured 3D correlation functions from two different spectrometer settings. The "horizontal" focus spectrometer setting optimizes the acceptance for R_{out}, while the "vertical" focus spectrometer setting is for R_{side}. The resolution in q_{out} and q_{beam} is $\approx$15 MeV/c and in q_{side} is $\approx$30 MeV/c.

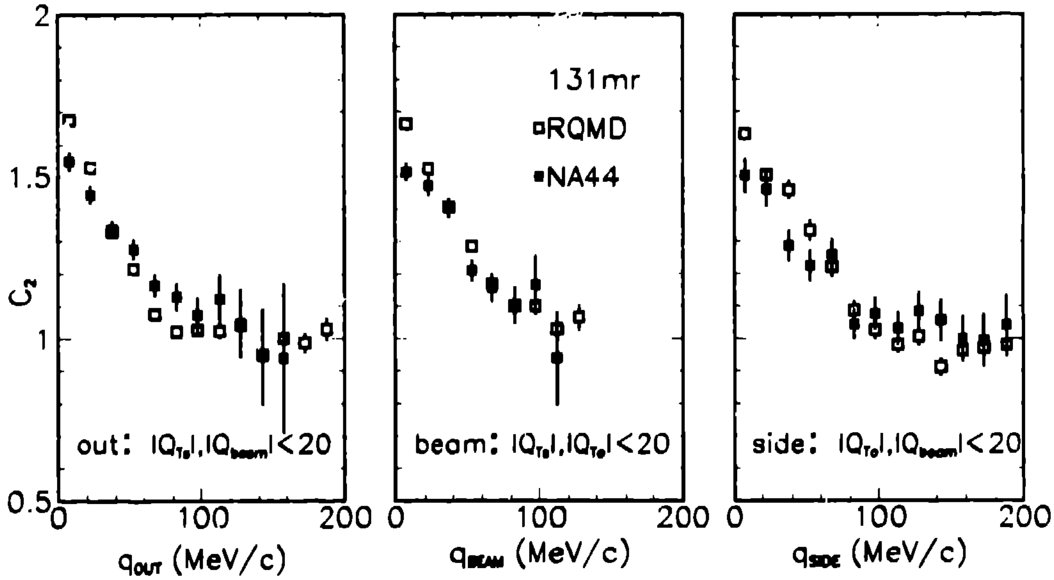

Figure 2: For 200 GeV/nucleon S+Pb collisions, the comparison of NA44 data and calculations based on the RQMD event generator. Calculations for the q_{out}, q_{beam}, and q_{side} components of the momentum difference are shown. Results for the 131 mr ("high p_T") spectrometer setting are shown.

Discussion

Fig. 1 compares NA44's measured correlation function at 44mr with the calculations based on RQMD[18]. If the point at the lowest value of q in each of the three panels is ignored, then the agreement between the data and calculation is reasonably good. Given the large systematic uncertainty (not shown in the errors bars) associated with this first data point, it is reasonable to neglect it in the comparision. If we do consider the first point in the comparison, then the RQMD calculation consistently gives a larger intercept as $q \to 0$ (λ). Fig. 2 compares NA44 data and the calculation for the 131mr spectrometer setting. As in fig. 1, the λ parameter in the calculation is slightly larger than the in the data but the calculation and data are very similar.

Fig. 3 compares size parameters from NA44[7, 10, 12] to size parameters fit to the RQMD correlations functions shown in figs. 1-2. In addition, the size parameters from the measured[10] and calculated K^+ correlation functions are shown. In fig. 3, the calculations for low p_T π^+ agree with the NA44 results for two of three size components, but the RQMD result is larger (by 3.4σ) than the NA44 result for R_{beam}. The RQMD result also agrees with the NA44 high p_T result for two of three size parameters, but the RQMD value of R_{out} is significantly larger than the NA44 result. The NA35 collaboration has also reported values of R_{out} from RQMD which are significantly larger than their experimental values[11]. For K^+, the NA44 and RQMD results are in good agreement.

When there are correlations between and emitted particle's position and momentum, the size parameter measured by interferometry (eq. 2) is generally different than the "true" size of the source (R_{gauss} in eq. 1). Studies with event generators[9, 18, 20, 24] and the kinematics of particle generation[25] both lead to the belief that such correlations do exist in high energy heavy ion collisions. Using an event generator, we can try to relate measured radius parameters, which come from a fit to a correlation function, to the "true" source size. One complication in the process is that, because the source position distribution is not a gaussian as in eq. 1, the "true" size does not always have an obvious definition.

Ideally the source "size" could be defined with one or two numbers, such as the transverse and longitudinal widths of the source position distribution, which would completely specify the source distribution. Unfortunately, for heavy ion collisions around 200 GeV/nucleon, the large fraction of pions which come from resonances such as the $\omega(783)$, η, and η' complicate such a definition[26]. These resonances add a long, approximately exponential, tail to the source distribution which extends to large distances. For positions around 23 fm, corresponding to the $\omega(783)$ lifetime, pions from $\omega(783)$ decay become the dominant contribution. For distances large compared to the $\omega(783)$ lifetime, the dominant components become first pions from η' decay, then the η decay. The

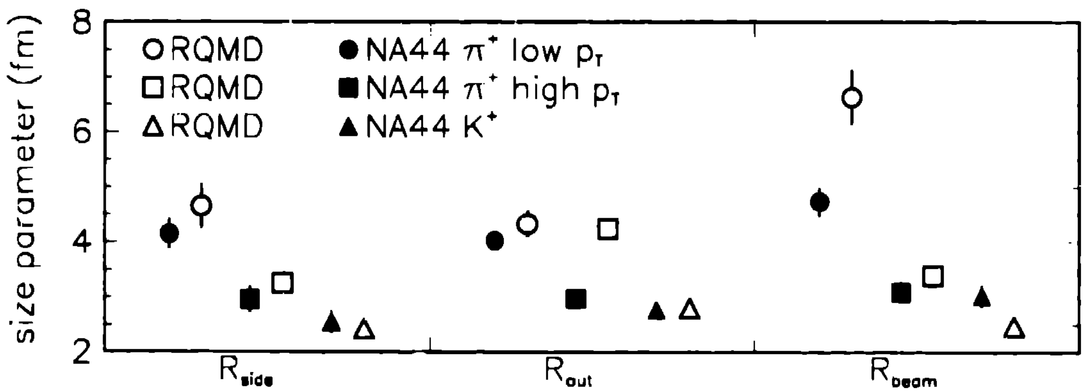

Figure 3: The size parameters, for 200 GeV/nucleon S+Pb, based on fits to 3 dimensional correlation functions, for low p_T π^+ (solid circles), high p_T π^+ (solid squares), and for K^+ pairs (solid triangles) from NA44. The corresponding fit parameters from the correlation functions calculated from RQMD are shown as open symbols.

NA44 detector's finite momentum resolution makes the NA44 experiment insensitive to structure in the correlation function finer than ≈10 MeV/c, so it is correspondingly insensitive to sizes larger than 20 fm ($\approx \hbar c/10$ MeV/c). Because the spectrum of pions from resonance decays is "softer" than the spectrum of primary pions, resonance contributions can be substantially reduced by measuring at higher p_T.

There are not as many long-lived resonances which produce K^+'s. A large fraction of all K^+ come from K^* decay, with the ω becoming more important at $x \approx 16$ fm. The K^* lifetime is around 4 fm/c, which can contribute to the "size" measured by interferometry. However, according to RQMD, the slope of the p_T spectrum of K^+ from K^* decay is similar to the overall slope. Therefore the K^* contribution can not be easily eliminated by measuring at higher p_T. On the other hand, the ω contribution can be largely eliminated by measuring above 800 MeV/c.

parameter	K^{++}	π^{++} 44 mr	π^{++} 131 mr
$\sigma(beam)$	2.1	3.5	3.4
$\sigma(trans.)$	2.4	3.4	3.5
$\sigma(time)$	5.0	5.0	5.2

Table 1: Standard deviations from Gaussian fits to the source position distributions in the beam, transverse, and time coordinates from RQMD. The values are given in fm.

One simple definition of the "size" comes from a gaussian fit to the source position distribution from RQMD. The gaussian fit generally fails in the tails of the distributions where resonances dominate, but is a reasonable representation of the transverse position distribution. The shapes of the longitudinal and time distributions are not well described by a gaussian. If the source distribution is restricted to the same range of y and p_T values as in covered by the NA44 spectrometer in each of its settings, the RQMD size parameters shown in table 1 can be calculated. The transverse, beam, and time widths are shown. The parameters are measured in the frame of reference with half the beam rapidity. With these definitions, the K^+ source size is smaller than the π^+ source size, while the π^+ size does not vary much with p_T. The observed p_T dependence of the π^+ source size parameters from both the data and RQMD (fig. 2) comes partially from the additional cut (not included in table 1) on azimuthal angle. At the high p_T setting, the NA44 spectrometer tends to see particles from the side of the source closest to the spectrometer[26] reducing the apparent source size from interferometry. This behavior is consistent with flow.

There are several problems associated with the Coulomb correction to two-pion correlation functions. The Gamow factor is normally used in the correction for the Coulomb interaction (repulsion) between the two particles. The Gamow factor is

$$G(\eta) = \frac{2\pi\eta}{\exp(2\pi\eta) - 1} \tag{3}$$

where $\eta = \alpha m_\pi / q_{INV}$, $\alpha \approx 137$ is the fine structure constant, and $q_{INV} = \sqrt{(-q \cdot q)}$ is the Lorentz invariant relative momentum. However, the Gamow factor is an approximation for a point source. Many experimental groups have used this approximation rather than a correction factor calculated with Coulomb wavefunctions. The advantages of the Gamow factor are its simplicity and, unlike the correction based on Coulomb wavefunctions, it does not require knowledge of the source size – which is what is being measured. Therefore using a Coulomb wave requires an iterative fitting process when determining the source radius parameters. In general, the Gamow factor overcorrects the correlation function[27].

A second problem occurs with the Gamow factor and the full Coulomb wavefunction calculation. Many of the pions come from the decay of long-lived resonances. About 9% of pions in the NA44 spectrometer acceptance at the low p_T setting come from the decay of the η and η' resonances[26]. The lifetimes of these resonances are $\approx$ 170000 fm/c and $\approx$ 1000 fm/c, respectively – so they decay far from the source of pions. When a pion pair contains one pion from the decay of these long-lived resonances ($\approx$ 18% of pairs), there is very little Coulomb interaction between the particles. In this case the Gamow factor (which assumes the particles came from a point source) is clearly an overcorrection[27]. If the full Coulomb wave calculation assumed the correct source shape, including the various long-lived resonances, it would be possible to make this correction properly. However, the exact source shape is not known experimentally and

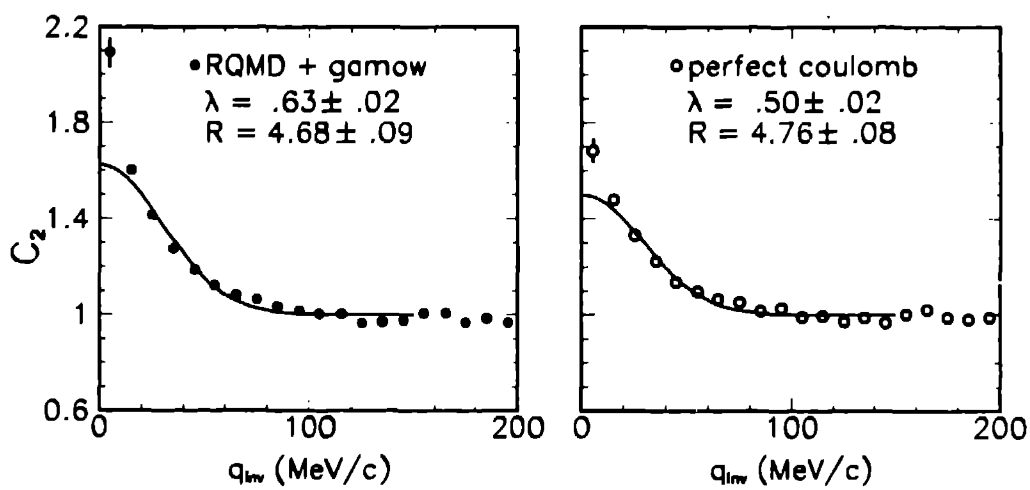

Figure 4: Based on calculations with RQMD for 200 GeV/nucleon S+Pb collisions, the $\pi^+\pi^+$ correlation function calculated using Coulomb waves in the original calculation but corrected with the Gamow factor (left side) and calculated with a "perfect" Coulomb correction (right side). The calculation with Coulomb waves and the Gamow factor (right side) is the "normal" calculation which is used in the other plots shown in this paper.

a gaussian form (eq. 1) is normally assumed in making the correction. The gaussian form does not contain the long tails to the distributions from resonance decays and therefore overcorrects the data also. Because a finite size is assumed, the overcorrection is smaller for the full Coulomb correction than for the gamow correction.

Fig. 4 shows a calculation based on RQMD which illustrates the problems in the Gamow correction. The left side of the plot is the "normal" RQMD calculation. A "normal" RQMD calculation takes pion pairs from the single particle distribution and adds the effects of (two-particle) Bose-Einstein correlations along with effects due to the Coulomb and strong interactions between the pions. The Coulomb interactions are added by using Coulomb wave functions in place of plane waves. The Coulomb interactions are then corrected in the calculated correlation function using the Gamow factor. In the model this approximation is not necessary. However, the goal is to compare to the experiment, which has used this approximation, so it is normally used with the calculation too. The right side of fig. 4 shows the results of an RQMD calculation with a "perfect" Coulomb correction. The "perfect" Coulomb correction is made by ignoring the Coulomb interaction when calculating the correlation function meaning that it does not have to be corrected. This "perfect" correction is not feasible for real data. The perfect Coulomb correction has an intercept at $q_{INV} = 0$ which is reasonable given the resonance fraction in the RQMD events (about 6% η, 3% η', and 12% ω). The Gamow corrected calculation has an intercept which is too large. Neither of the fits shown in fig. 4 is good in the low q_{INV} region - the shape of the calculated correlation function is not gaussian. However, the fit parameters do reflect the overcorrection from the Gamow factor - λ is significantly larger in the fit to the Gamow corrected calculation than in the "perfect" calculation.

Conclusions

Source size parameters calculated from RQMD are in reasonable agreement with the results from NA44. If RQMD is then used to attempt to relate the source size parameters with the "true" source size, we see that the "true" source size is difficult to define with a single number. The widths of the RQMD source distributions for particles within the spectrometer's acceptance show a K^+ source which, like the size parameters from the correlation functions, is smaller than the π^+ source. One example of the overcorrection introduced by the the "gamow" correction was shown. Long-lived resonances contribute to this overcorrection.

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